Electron localization and superconductivity in narrow aluminum films

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An increase in the resistance of narrow aluminum films has been observed experimentally with decreasing temperature. This resistance increase is typical of electron localization effects in quasi-one-dimensional systems. A superconductivity mechanism becomes predominant at lower temperatures.

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In thin metal films having a high resistivity, i.e., a short mean free path l, a minimum can be expected to appear on the temperature dependence of the resistance and to subsequently increase in size.[1] This effect is currently believed to result from either a localization of electrons[2,3] or an electron-electron interaction in the presence of impurity scattering.[4,5] As the temperature is lowered to $T=0$, the resistance of such a two-dimensional film or one-dimensional filament should, in principle, tend toward infinity; i.e., the samples should become nonconducting dielectrics.[2,3] On the other hand, as T approaches zero in a metal film or a filament, superconducting pairing may occur, and the resistance of the sample may drop to zero. We are thus led to ask whether these states can coexist and which will become predominant as the temperature is lowered. In this letter we are reporting measurements for narrow, thin films of aluminum with surface resistivities $R_\square = 10^2-10^3\ \Omega$ ($\rho = 10^{-4}-10^{-3}\ \Omega$ cm) near but below the localization threshold, which determines the maximum metallic surface resistivity of the film ($R_{\square\max} \approx 3 \cdot 10^4\ \Omega$; Ref. 6). The results show that such films initially exhibit localization effects and then go superconducting.

The samples in the present experiments were long, narrow, thin films of aluminum (the length was $L \sim 500\ \mu$m; the width was $w = 0.7$–$0.8\ \mu$m; and the thickness was $d \sim 100$ Å), deposited at room temperature on a crystalline quartz substrate. This deposition was carried out in a vacuum of $10^{-3}-10^{-4}$ Pa at a rate ~ 10 Å/s through masks of a thick tin film with a narrow slit; the masks were removed after the deposition.[7] The resistance of the film was monitored during the deposition, and the deposition was stopped as soon as $R_\square$ reached the desired value. After the film was removed from the vacuum chamber and exposed to the air, its resistivity increased exponentially, over a period of 10 days, to a value 30% higher than its original value. Electron microscopy revealed that the films were solid with a grain size less than 50 Å.

The resistivity of the films was measured from room temperature down to 1.5 K by a four-probe method with a given current at a frequency ~ 1 kHz. For precise

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measurements of small changes in the resistivity, we used a comparison bridge, which had a relative error of 3×10^{-5} at the measurement current of 10 nA. The error in the temperature measurements was $\sim 10^{-2}$ K at liquid-helium temperatures and 5×10^{-1} K at liquid-nitrogen temperatures. Curves of $R(T)$ were recorded on an x, y chart recorder.

Figure 1 shows $R(T)$, the temperature dependence of the resistivity, for a sample with $R_\square = 230\ \Omega$ (sample No. 1) and for one with 635 Ω (No. 2). We see that R initially decreases, then goes through a minimum, increases to a maximum, and drops sharply to zero (Fig. 1b). Let us take a closer look at each of these parts of the temperature dependence. A detailed study of the initial decrease in R, from room temperature down to the temperature of the minimum resistivity, $T_{\min}$, revealed a behavior $R(T) \sim T$ down to $T \approx \Theta/2$ (Θ is the Debye temperature; in Al, $\Theta = 428$ K). From the Debye temperature down to $T_{\min}$, the behavior is $R(T) \sim T^5$. This behavior is typical of a metallic conductivity. We observed the minimum on the $R(T)$ curves at quite high temperatures, $T \sim 100$ K; this is again a reasonable result, since it can be shown that $T_{\min}$ is on the order of Θ, which is quite high for aluminum. The position of the minimum, i.e., the temperature $T_{\min}$, furthermore depends on $R_\square$: As $R_\square$ increases, $T_{\min}$ shifts to a higher temperature (to $T_{\min} = 41$ K for sample No. 1 and to $T_{\min} = 77$ K for sample No. 2).

Thereafter, over a rather broad temperature range from $T_{\min}$ down to 10 K, we observe an increase in R. The extent to which R increases with respect to $R_{\min}$ also depends on $R_\square$; specifically, the increase is greater for the samples having the larger values of $R_\square$. For sample No. 2, the increase in R was so pronounced that $R_{\max}$ exceeded R_{300}. Figure 2 shows the regions of the temperature dependence in which ΔR increases, plotted as a function of $T^{-1/2}$. We see that this dependence is very accurately linear. The curves of $\Delta R \sim \ln(1/T)$, on the other hand, are definitely nonlinear. In these narrow films, therefore, we are seeing $\Delta R \sim T^{-1/2}$—a behavior char-

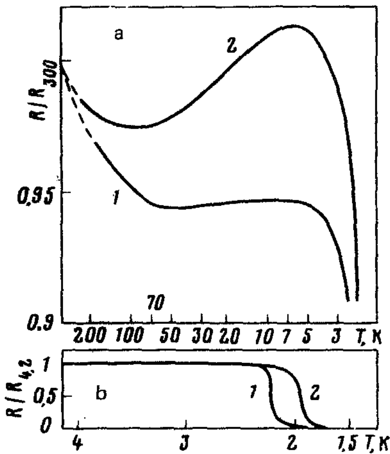

FIG. 1. Temperature dependence of the resistance of aluminum films No. 1 and 2. The surface resistivity and the resistance of sample No. 1 at room temperature are $R_\square = 230\ \Omega$ and $R = 48.1$ K Ω; the corresponding values for sample No. 2 are $R_\square = 635\ \Omega$ and $R = 182.5$ K Ω.

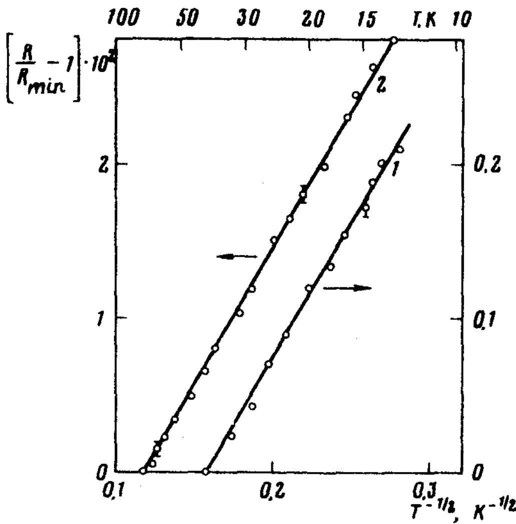

FIG. 2. Temperature dependence of the relative increase in the resistance, $R/R_{min} - 1$, of aluminum films No. 1 and No. 2.

acteristic of the quasi-one-dimensional case.[1,8] The characteristic dimension determining the dimensionality of the system is the length $L_i \approx \sqrt{D\tau_i}$ for the localization mechanism and the length $L_c \approx \sqrt{\hbar D/kT}$ for the interaction mechanism.[5] Estimates based on our experimental data yield $L_i \approx 1$ μm (with a diffusion coefficient $D \simeq 10$ cm^2/s and an inelastic-relaxation time $\tau_i \approx 10^{-9}$ s) and $L_c \approx 300$ Å at $T = 10$ K. In other words, because of the rather long inelastic-relaxation time of the electrons, the localization length in the aluminum films is also quite large, greater than the width of our films ($w = 0.7$-0.8 μm). For these films, therefore, the condition for a quasi-one-dimensional geometry is satisfied for the localization case, $w < L_i$, but not for the case of the electron-electron interaction, $w \gg L_c$. In other words, these films must be regarded as two-dimensional with respect to the interaction mechanism,[4,5] and in them we should expect to find $\Delta R \sim \ln(1/T)$. The experimental dependence, on the other hand, is $\Delta R \sim T^{-1/2}$, and this result apparently means that a localization mechanism is primarily responsible for the increase in ΔR.

The increase in R slows at $T \sim 10$ K; there is a maximum, and then R decreases with the subsequent superconducting transition (Fig. 1b). These results unambiguously show that after the localization effects (or the interaction effects) are observed, between T_{min} and at 10 K, a new mechanism comes into play: superconducting pairing. This new mechanism ultimately reduces the resistance of the film to zero. The critical temperature of these films, taken here to be the temperature at which the resistance has dropped by a factor of 2, is 2.21 K for sample No. 1 and 1.95 K for sample No. 2. With increasing $R_\square > 200$ Ω, the critical temperature T_c decreases slightly, as in Ref. 9. The superconducting fluctuations begin to have a significant effect on $R(T)$ at temperatures as high as $T \approx 10$ K. Larkin[10] has derived a theory for the simultaneous effects of superconducting fluctuations and localization on the magnetoresistance of metal films. Working from the results of that paper for the case

$H=0$, we can find the temperature at which these two mechanisms become comparable in effect [this temperature corresponds approximately to the maximum on our $R(T)$ curves]. This estimate yields $T_{max} = 2.7T_c$, i.e., 6.5 K for sample No. 1 and 5.2 K for sample No. 2, in good agreement with the experimental values of T_{max}, 8.0 and 5.9 K, respectively. A detailed study of the region of the maximum on the $R(T)$ curves will yield more accurate results on the contribution of the superconductivity fluctuations and on several other parameters.[10] The results described above suggest a change in the nature of the conductivity of these metal thin films with decreasing temperature. The metallic resistance of these films, which is decreasing over the range from 300 to 100 K, becomes supplemented at $T \sim 100$ K by an increment ΔR which is caused by either the localization of some of the electrons or interaction effects. As the temperature of the superconducting transition, T_c, is approached, the increment ΔR is canceled out to a progressively greater degree by the fluctuational superconductivity. These two mechanisms coexist over the interval 10–2.2 K. Below this temperature interval, the superconducting channel shunts all the other conductivity channels, and the resistance of the film drops to zero. Further theoretical and experimental study is required to determine how the localization effects interact with the change caused in the state density near the Fermi surface by the interaction with the competing mechanism of superconducting pairing, for which these states are very important. How these effects depend on the film resistance also requires further study.

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